# Physics Results from COMPASS

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**Abstract**

The COMPASS Experiment at the CERN SPS has a broad physics program focused on the nucleon spin structure and on hadron spectroscopy, using muon and hadron beams. Main objectives for the spin program with the muon beam are the direct measurement of the gluon contribution to the spin of the nucleon, semi-inclusive measurements, and the measurement of the transverse spin distribution $\Delta_{\rm T}{\rm q}({\rm x})$. The COMPASS apparatus consists of a two-stage large acceptance spectrometer designed for high data rates and equipped with high-resolution tracking, particle identification and electromagnetic and hadronic calorimetry.
The data taking is ongoing since 2002 and till now was mainly devoted to the spin programme using a 160 $\mathrm{GeV}/c$ naturally polarized, $\mu^+$ beam and a polarized $^6\mathrm{LiD}$ target. First physics results from the 2002 and 2003 runs are presented.

## 1 Introduction

The COMPASS[1] experiment is focused to a deeper understanding on how the constituents contribute to the spin of the nucleon. The main goal is a direct measurement of the gluon polarization $\Delta\mathrm{G}/\mathrm{G}$, obtained by measuring the spin dependent asymmetry of open charm production in the photon-gluon process. The determination of the transversity distribution function $\Delta_{\rm T}{\rm q}({\rm x})$ and studies of transverse spin effects; accurate measurements of the flavor decomposition of the quark helicity distributions, vector meson exclusive production and $\Lambda$ physics are also important parts of the program. The hadron spectroscopy is dedicated to the measurements of the mass and decay patterns of light hadronic systems and leptonic decays of charmed mesons, as well as $\pi$ and K polarizabilities (Primakoff reactions), extensive meson spectroscopy to investigate the presence of exotics states.

The experiment, performed by a collaboration of about 270 physicists from 27 institutes and 11 countries, was set-up in 1998–2000 and a technical run took place in

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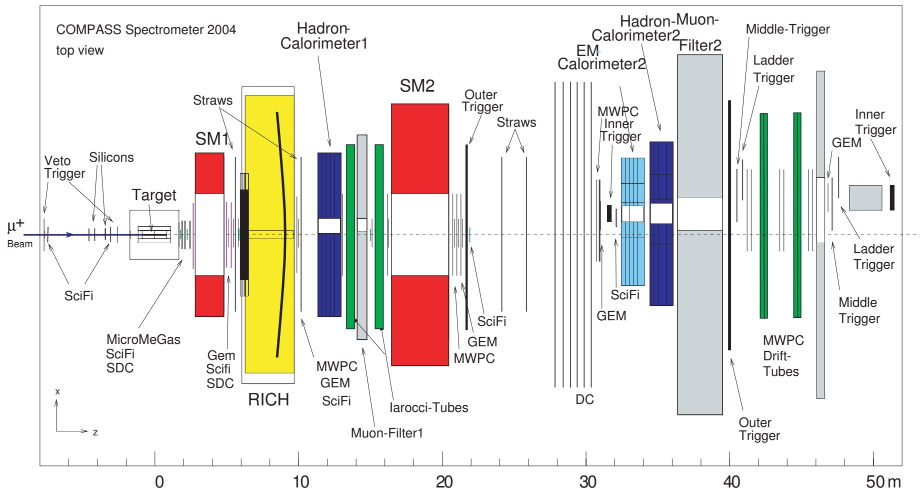


Figure 1: Top view of the lay-out of the spectrometer for the COMPASS experiment in 2004. The labels and the arrows refer to the major components of the tracking, trigger, and PID systems.

2001. The runs from 2002 to 2004 were mainly devoted to the spin programme with a polarized muon beam and a polarized $^6$LiD target. After the 2005 technical stop of CERN, COMPASS will run at the SPS at least until 2010.

The talk is focused on the results of 2002 and 2003 runs, during which a total of 500 TB of data have been collected.

## 2 The COMPASS apparatus

The COMPASS experiment has been set up at the CERN SPS M2 beam line. It combines high rate beams with a modern two stage magnetic spectrometer[2]. Both stages are equipped with hadronic calorimetry and muon identification via filtering through thick absorbers. In the first stage a RICH detector is also installed, allowing the identification of charge hadrons up to 40 GeV. Detectors, electronics and data acquisition system are able to handle beam rates up to $10^8$ muons/s and about $5{\times}10^7$ hadrons/s with a maximal interaction rate of about $2{\times}10^6$/s. The triggering system and the tracking system of COMPASS have been designed to stand the associated rate of secondaries, and use state-of-the-art detectors. Also, fast front-end electronics, multi-buffering, and a large and fast storage of events are essential.

The layout of the spectrometer for the 2004 running period is shown in Fig. 1. The experiment has been run at a muon energy of 160 GeV. The beam is naturally polarized by the $\pi-$decay mechanism, and the beam polarization is estimated to be 76%. The beam intensity is $2 \times 10^8$ muons per spill (4.5 s long).

We use the polarized target system of the SMC experiment[4], which allows for

Table 1: Trackers performances in the 2002 run.

| Detector | coordinates | efficiency | resolution | timing |
|---|---|---|---|---|
| Scintillating fibers | 21 | 94 % | 130 $\mu$m | 0.45 ns |
| Micromegas | 12 | 95 - 98 % | 65 $\mu$m | 8 ns |
| GEM | 40 | 95 - 98 % | 50 $\mu$m | 12 ns |
| SDC | 24 | 94 - 97 % | 170 $\mu$m | |
| Straw tubes | 18 | $>$ 90 % | 270 $\mu$m | |
| MWPC | 32 | 97 - 99 % | | |
| W4/5 | 8 | $>$ 80 % | | |

two oppositely polarized target cells, 60 cm long each. The PT magnet can provide both a solenoid field (2.5 T), to hold the longitudinal (with respect to the beam direction) polarization, and a dipole field (0.5 T), needed for adiabatic spin rotation and for holding the transverse polarization. Use of two different target materials, $NH_3$ as proton target and $^6$LiD as deuteron target, is foreseen. Polarizations of 85% and 50% have been reached, respectively. In so far we have used $^6$LiD because its favorable dilution factor[5] of $>$0.4 is particularly important for the measurement of $\Delta G/G$. In 2006 the installation of a new PT magnet build by Oxford-Danfysik, with an increased inner bore radius matching the full acceptance of the spectrometer ($\pm 180$ mrad), is foreseen. As a result, an increased acceptance at large $x_{\mathrm{Bj}}$ and a better sensitivity to the charm channel will improve the figure of merit of the experiment.
Different tracking devices are used to cope with different fluxes and to fit the needed resolution. The small area trackers (SAS), sitting on or close to the bean line, consist of several stations of scintillating fibers, silicon detectors, micro-pattern gaseous detectors like Micromega[6] and GEMs[7]. Large area tracking (LAS) devices are made from gaseous detectors (the Saclay Drift Chambers, Straw tubes[8], MWPCs, and the W4/5 Drift Chambers) placed around the two spectrometer magnets. Table 1 summarizes the spatial resolution and the timing properties of the tracking detectors, as derived from the 2002 data. Muons are efficiently identified by large detector planes placed before and after a 60 cm thick iron absorber. Aluminum Iarocci-type limited streamer and drift tubes planes are used in the LAS and in the SAS respectively.

Hadron identification in the LAS is provided by RICH-1[9], designed to separate $\pi$ and K, over the whole LAS angular acceptance up to 60 GeV. RICH-1 consists of a 3 m long $C_4F_{10}$ radiator at atmospheric pressure, a wall of spherical mirrors (3.3 focal length) covering an area of $>$20 m$^2$ and two sets of far UV photon detectors placed above and below the acceptance region. The Cherenkov photons are detected by MWPCs equipped with CsI photo-cathodes [10], segmented in 83000, $8 \times 8$ mm$^2$ pads read-out by a system of front-end boards [11] with local intelligence.

The trigger is formed by two hadron calorimeters and several hodoscope systems. 2 ns wide coincidences between more than 500 elements select the scattered muons in the kinematics region of interest, on the bases of target pointing and energy release. An hadron shower in the hadronic calorimeter provides more selective triggering. The

overall typical trigger rate was 5 kHz with a dead time of about 7%. The acceptance in $Q^2$ goes from quasi-real photons $\sim 10^{-4}$ $(\mathrm{GeV/c})^2$ up to $\sim 100$ $(\mathrm{GeV/c})^2$, while $x_{\mathrm{Bj}}$ is from $10^{-4} (\simeq 4 \times 10^{-3}\,\mathrm{for}\,\mathrm{Q}^2 > 1) < x_{\mathrm{Bj}} < 0.7$.

The readout system[12] uses a modern concept, involving highly specialized integrated circuits. The readout chips are placed close to the detectors and the data are concentrated at a very early stage via high speed serial links. At the next level high bandwidth optical links transport the data to a system of readout buffers. The event building is based on PCs and Gigabit or Fast Ethernet switches and is highly scalable. This high performance network is also used to transfer data, via optical link, to the Central Data Recording (CDR) in the computer center for database formatting, reconstruction, analysis and mass storage.

The computing power needed to process the huge amount of data ($\sim$300 TB/year) is about 100 kSI2k. The raw data processing is centrally performed at CERN, while the DST and mDST analysis, as well as the large Monte Carlo production are done on satellite farms in the major home institutes. The event reconstruction is performed by a fully object oriented program, with a modular architecture, written in C++ (CORAL). C++ has also been used to write the analysis program PHAST, while the Monte Carlo program COMGEANT is based on GEANT3.

# 3 First Physics Results

Many physics channels are under investigation, and important flavors of the ongoing work were given in the parallel sessions:
– $A_1^d$, the virtual photon asymmetry in both inclusive and semi-inclusive DIS[13],
– $\Delta\mathrm{G}/\mathrm{G}$ from open charm and from production of pair of high-$p_T$ hadrons[14],
– transverse spin asymmetries[15, 16],
– exclusive vector meson production to test s-channel helicity conservation[17],
– spontaneous $\Lambda$ polarizations[18, 19].
Due to the limited space, in this contribution only some of the relevant results of items 1–3 will be summarized.

## 3.1 Inclusive and Semi-Inclusive Asymmetries

The preliminary results from COMPASS, based on 2002-2003 data, are shown in figure 2, where results from previous measurements are also given[20, 21, 22]. The COMPASS data are in good agreement with the other data sets, and are compatible with zero in the low-$x$ region (fig. 2(a) and (b)). Moreover, the COMPASS data at low-$x$ (fig. 2(b)) have statistical errors already smaller than SMC, thanks to higher luminosity and dilution factor, and will contribute to improve the precision on the spin dependent structure function $g_1^d(x)$ and on its first moment $\Gamma_1^d$. Figures 2(c) and (d) show semi-inclusive asymmetries $A_1^h$ for hadrons of positive charge (c) and of negative charge (d), compared with existing data[23, 24]. In this case statistical errors at low-$x$ are also smaller than previous measurements. Those hadrons samples are dominated by pions ($\sim 80\%$), and at this stage of the analysis the RICH information is not yet used. Even by using PID a full flavor decomposition from the deuteron data alone is not possible

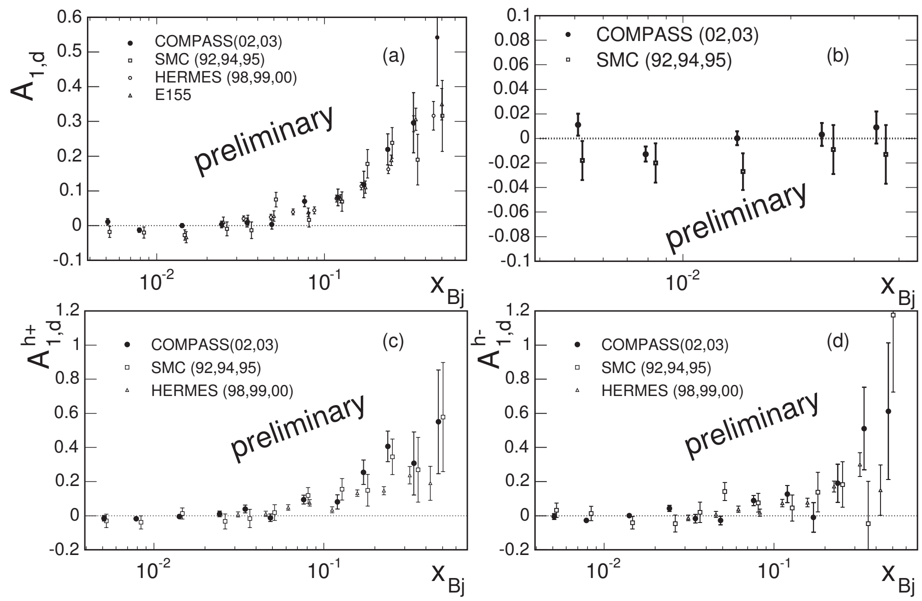


Figure 2: (a) Measured asymmetry $A_1^d$ from COMPASS 2002-2003 runs compared with the existing data. (b) Same measurement for the low-$x$ region compared with SMC data only. (c) Semi-inclusive spin asymmetry $A_1^h$ as a function of $x$ for positively charged hadrons. (d) Semi-inclusive spin asymmetry $A_1^h$ as a function of $x$ for negatively charged hadrons.

and there is the needs to extent the measurement by collecting data also with a proton target; nevertheless one can extract $\Delta u + \Delta d$, $\Delta\bar{u} + \Delta\bar{d}$ and from kaon samples $\Delta s = \Delta\bar{s}$, i.e. the the strange quark helicity distribution function. With the accumulated statistics from 2002 to 2004, COMPASS will extend by one order of magnitude, in the low-$x$ region, the existing results[25] on $\Delta s(x)$, decreasing the uncertainties on the first moment.

### 3.2 Gluon polarization $\Delta G/G$

In COMPASS the gluon polarization $\Delta \mathrm{G}/\mathrm{G}$ is accessed by identifying the photon-gluon fusion process, tagged either by open-charm production or by the production of pair of high-$p_T$ hadrons.

Open-charm events are selected by reconstructing $\mathrm{D}^0$ and $\mathrm{D}^*$ mesons from their decay products, i.e. $\mathrm{D}^0 \to \mathrm{K}\pi$ and $\mathrm{D}^* \to \mathrm{D}^0\pi^0 \to \mathrm{K}\pi\pi^0$. In the first case, cuts on the K direction in the $\mathrm{D}^0$ rest frame ($|\cos(\theta^*_{\mathrm{K}})| < 0.5$) and on the $\mathrm{D}^0$ energy fraction ($\mathrm{z_D} = \mathrm{E_D}/\mathrm{E}_{\gamma^*} > 0.25$) are needed to reduce the background still dominant. The second case is much cleaner given the unique kinematics. Figure 3(a) shows the $\mathrm{D}^0$ peak reconstructed from the 2003 run, by selecting $\mathrm{D}^0$ coming from $\mathrm{D}^*$ decays. The projected error from the open charm, including all the 2002–2004 data is $\delta\,(\Delta\mathrm{G}/\mathrm{G}) = 0.24$.

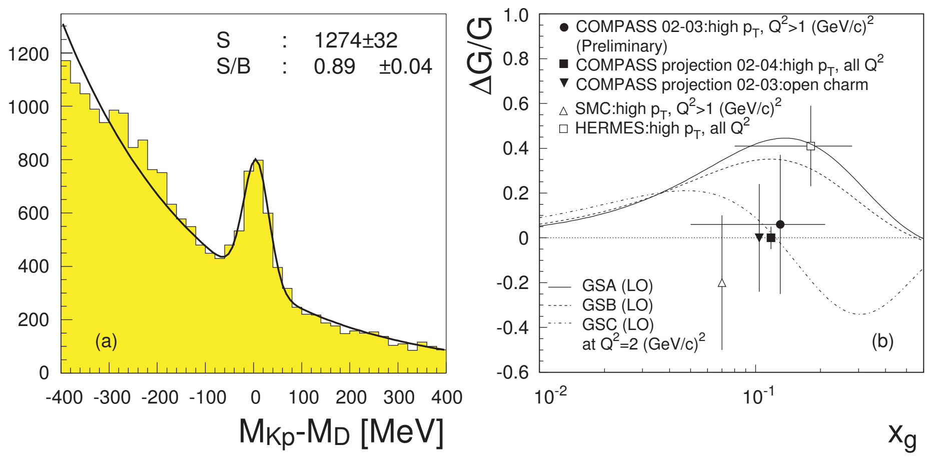


Figure 3: (a) Reconstructed $\mathrm{D}^0$ in the $\mathrm{K}\pi$ invariant mass distribution tagged from the $\mathrm{D}^*$ decay. (b) Preliminary result for $\Delta\mathrm{G}$ from COMPASS high-$p_T$ production and $Q^2 > 1$ $(\mathrm{GeV}/c)^2$, together with the results from HERMES ($\langle Q^2 \rangle = 0.06$ $(\mathrm{GeV}/c)^2$) and SMC ($Q^2 > 1$ $(\mathrm{GeV}/c)^2$). Also shown are the projected error bars for the open charm high-$p_T$ (all $Q^2$) for the whole 2002–2004 data. The curves show the parametrization A–C of Ref.[31].

$\Delta\mathrm{G}/\mathrm{G}$ from pair of high-$p_T$ hadrons has, compared to open charm, the advantage of a larger statistics, even if the extraction of the gluon polarization is more difficult due to the contribution to the asymmetry of competitive processes. Selecting events with $Q^2 > 1$ $(\mathrm{GeV}/c)^2$ drastically cut the contribution from resolved photons, at the price of a $\sim 1/10$ reduction of the data sample. Selecting events with high-$p_T$ hadrons reduces the contribution from the leading order process $\gamma q \to q$ (LO), and increases the QCD-Compton process $\gamma q \to \gamma q(gq)$, and the photon-gluon fusion (PGF) creation of a light $q\bar{q}$ pair. An additional selection $x_{\mathrm{Bj}} < 0.05$ allows to restrict the data to a region where $\Delta q/q$ is closed to 0, and therefore the contribution to the asymmetry from background processes (LO and QCD-Compton) can be neglected. With this assumption we can relate the preliminary virtual photon-deuteron asymmetry $A^{\gamma^* d}$ resulting for high-$p_T$ pair production from the 2002-2003 data at $Q^2 > 1$ $(\mathrm{GeV}/c)^2$ ($A^{\gamma^* d} = -0.015 \pm 0.080\,(\mathrm{stat}) \pm 0.013\,(\mathrm{syst.})$) to $\Delta\mathrm{G}/\mathrm{G}$:

$$A^{\gamma^* d} = \frac{A_{LL}^{\mu d \to hhX}}{D} \approx \left\langle \frac{\hat{a}_{LL}^{PGF}}{D} \right\rangle \left\langle \frac{\Delta \mathrm{G}}{\mathrm{G}} \right\rangle \frac{\sigma^{PGF}}{\sigma^T}$$

where $\hat{a}_{LL}$ is the analyzing power of the process at the partonic level, $D$ is the depolarization factor and $\sigma^{PGF}/\sigma^T$ is the fraction of PGF processes in the selected sample. For COMPASS we have estimated, from the Monte-Carlo of the experiment, using LEPTO[26] as generator, $\langle \hat{a}_{LL}/D \rangle = -0.74 \pm 0.05$ and $\sigma^{PGF}/\sigma^T = 0.34 \pm 0.07$, allowing the extraction of $\Delta\mathrm{G}/\mathrm{G} = 0.06 \pm 0.31\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{sys.})$ at a mean gluon momentum fraction $x_g = 0.13$.

For the whole period 2002-2004 one can determine $\Delta\mathrm{G}/\mathrm{G}$ with an accuracy $\simeq 0.17$ for events with $Q^2 > 1$ (GeV$/c$)$^2$, while allowing for all $Q^2$ gives a statistical error of 0.05. The preliminary result from high-$p_T$ are shown in figure 3(b), together with the measurements from HERMES[27] and SMC[28] .

### 3.3 Collins and Sivers Effects

The chirally-odd transversity distributions $\Delta_\mathrm{T}\mathrm{q}(\mathrm{x})$can be accessed, as suggested by Collins[29], in semi-inclusive interactions of leptons off transversely polarized nucleons in combination with the chirally-odd fragmentation function $\Delta D_q^h(z, p_T)$. At first order the measured azimuthal asymmetry $A_\mathrm{Col}$ can be written as:

$$\mathrm{A}_\mathrm{Col} = \frac{\sum_a e_a^2 \cdot \Delta_T q_a(x) \cdot \Delta D_a^h(z, p_T)}{\sum_a e_a^2 \cdot q_a(x) \cdot D_a^h(z)} = \frac{1}{\sin\Phi_\mathrm{C} D_{NN} f} \cdot \frac{N^+ - N^-}{N^+ + N^-}$$

A different mechanism may also give rise to an asymmetry in the scattering of leptons off transversely polarized nucleon. Accounting for an intrinsic momentum $k_T$ dependence of the quark distribution in the nucleon $\Delta_0^T q_a(x, k_T^2)$ may induce an azimuthal asymmetry (Sivers effect[30]) in:

$$\mathrm{A}_\mathrm{Siv} = \frac{\sum_a e_a^2 \cdot \Delta_0^T q_a(x, k_T^2) \cdot D_a^h(z)}{\sum_a e_a^2 \cdot q_a(x) \cdot D_a^h(z)} = \frac{1}{\sin\Phi_\mathrm{S} D_{NN} f} \cdot \frac{N^+ - N^-}{N^+ + N^-}$$

To measure transverse asymmetries, COMPASS has taken SIDIS data with the $^6$LiD polarized orthogonally to the incoming $\mu$ momentum for about 20% of the running time.

Figure 4 shows preliminary results of the first ever measured single hadron Collins asymmetry on a deuteron target, separately for positive and negative hadrons produced in the struck quark fragmentation as a function of $x_\mathrm{Bj}$, $z = E_h/(E_\mu - E_{\mu'})$ and the transverse momentum of the hadron $p_T$ (first row). The Sivers asymmetry, also on a deuteron target is shown in the second row. The small values of the Collins asymmetries at all $x$ might imply either a cancellation between the proton and the neutron asymmetries, or a small Collins effect in the fragmentation $\Delta D_q^h$. Also the Sivers asymmetry is small and, with these statistical errors, compatible with zero, which may indicate a small value of $\Delta_0^T q$ in the covered $x$ range. These results are based on 2002 run only; the full analysis of the 2002-2004 data will allow to reduce the statistical errors by a factor of 2.

Other promising channels, such as the asymmetries in the two hadrons fragmentation[16], inclusive vector mesons production, and $\Lambda$ productions are also under study and will give soon new important insight in the nucleon spin structure.

## 4 Conclusion

The CERN COMPASS experiment is on the floor, taking data, since 2002. Many novel detectors and LHC techniques were integrated in the experiment and are performing according to expectations. The new and modern analysis system has also required large

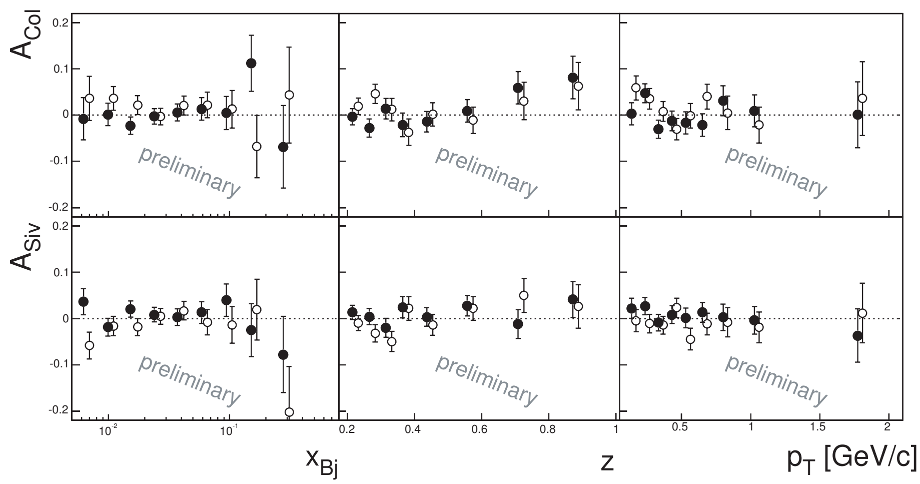


Figure 4: Collins (top) and Sivers (bottom) asymmetries as a function of $x_{\mathrm{Bj}}$, $z$ and $p_T$ for positively (open triangles) and negatively (closed squares) charged hadrons.

efforts within the collaboration, but is now running at full gears and very interesting results are coming.

First physics results have been produced and have been shown here and in the parallel sessions of this conference, while many others will appear in the near future. The first three years of data takin had shown that COMPASS has the complete potentiality to fully perform its broad physics programme, allowing CERN to bringing new pieces of information to the spin puzzle. After the accelerator technical stop of 2005, COMPASS will run till 2010.

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